

## Dynamics of line-driven disk winds

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**Abstract.** I review the main results from recent 2-D, time-dependent hydrodynamic models of radiation-driven winds from accretion disks in AGN. I also discuss the physical conditions needed for a disk wind to be shielded from the strong X-rays and to be accelerated to hypersonic velocities. I conclude with a few remarks on winds in hot stars, low mass young stellar objects, cataclysmic variables, low mass X-ray binaries, and galactic black holes and future work.

### 1. Introduction

A key constraint on any model for the origin of AGN outflows is the ionization balance. On one hand we observe very high luminosities in X-rays and the UV and on the other hand we observe spectral lines from moderately and highly ionized species. One wonders then how the gas avoids full photoionization and we see any spectral lines at all. Two mechanisms have been proposed to resolve the so-called overionization problem: (i) the AGN outflows have filling factors less than one and consist of dense clouds and (ii) the filling factors equal one but the outflows are shielded from the powerful radiation by some material located between the central engine and the outflow (e.g., Krolik 1999). Only limited citations will be possible due to space limitations; my apologies in advance.

One plausible scenario for AGN outflows is that a wind is driven from an accretion disk around a black hole. Radiation pressure due to spectral lines is one of the forces that have been suggested to accelerate outflows in AGNs.

Our understanding of how line-driving produces powerful high velocity winds is based on the studies of winds in hot stars (e.g., Castor, Abbott, Klein 1975, hereafter CAK). The key element of the CAK model is that the momentum is extracted most efficiently from the radiation field via line opacity. CAK showed that the radiation force due to lines,  $F^{rad,l}$  can be stronger than the radiation force due to electron-scattering,  $F^{rad,e}$  by up to several orders of magnitude (i.e.,  $F^{rad,l}/F^{rad,e} < M_{max} \approx 2000$ ). Thus even a star that radiates at around 0.05% (i.e.,  $1/M_{max}$ ) of its Eddington limit,  $L_E$  can have a strong wind.

To apply line-driven stellar wind models to AGN we have to take into account at least two important differences: (i) the difference in geometry – stellar winds are to a good approximation spherically symmetric, whereas the wind in AGN likely arises from a disk and is therefore axisymmetric; and (ii) the difference in the spectral energy distribution – hot stars radiate mostly the UV (the UV luminosity,  $L_{UV}$ , accounts for most of the total luminosity,  $L$ ), whereas

AGN radiate strongly both in the UV and X-rays ( $L_{UV}$  and  $L_X$  are comparable). The latter difference has two important consequences on UV line driving: not all AGN radiation contributes to driving, and even worse, the X-rays that do not contribute to UV line driving can ionize the gas and reduce the number of transition that can scatter the UV photons (in the case of a fully ionized gas,  $F^{rad,l} = 0$  and by definition  $M_{max} = 0!$ ).

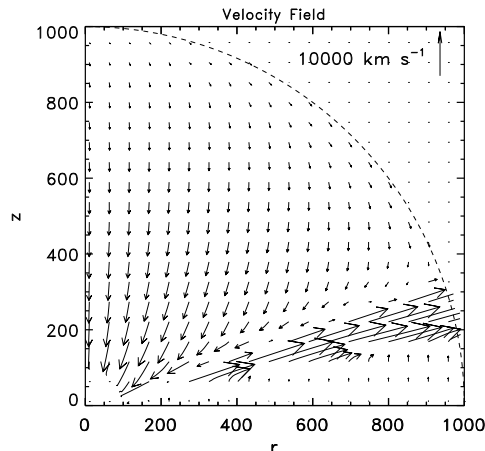
The consequences of the difference in geometry have been recently studied using 2-D axisymmetric numerical hydrodynamical simulations (e.g., Proga, Stone & Drew 1998, hereafter PSD98). These simulations were focused on cataclysmic variables (CVs), which as do hot stars, radiate mostly in the UV. In particular, PSD98 explored the impact upon the mass-loss rate,  $\dot{M}_w$  and outflow geometry caused by varying the system luminosity and the radiation field geometry. A striking outcome was that winds driven from, and illuminated solely by, an accretion disk yield complex, unsteady outflow. In this case, time-independent quantities can be determined only after averaging over several flow timescales. On the other hand, if winds are illuminated by radiation mainly from the central object, then the disk yields steady outflow. PSD98 also found that  $\dot{M}_w$  is a strong function of the total luminosity, while the outflow geometry is determined by the geometry of the radiation field. For high system luminosities, the disk mass-loss rate scales with the luminosity in a way similar to stellar mass loss. As the system luminosity decreases below a critical value (about twice the effective Eddington limit,  $L_E/M_{max}$ ) the mass-loss rate decreases quickly to zero. Matter is fed into the fast stream from within a few central object radii. In other words, the mass-loss rate per unit area decreases sharply with radius. The terminal velocity of the stream is similar to that of the terminal velocity of a corresponding spherical stellar wind, i.e.,  $v_\infty \sim$  a few  $v_{esc}$ , where  $v_{esc}$ , is the escape velocity from the photosphere. Thus the difference in geometry changes the wind geometry and time behavior but has less effect on  $\dot{M}_w$  and  $v_\infty$ .

Proga, Stone & Kallman (2000, hereafter PSK) made another step in studying line-driven winds from accretion disks. To assess how winds can be driven from a disk in the presence of very strong ionizing radiation (as in AGN) they adopted the approach from PSD98 with three major modifications: 1) calculation of the parameters of the line force based on the wind properties, 2) inclusion of optical depth effects on the continuum photons, and 3) inclusion of radiative heating and cooling of the gas. In next section I will review results from PSK and from related calculations by Proga & Kallman (2001, PK hereafter).

## 2. Hydrodynamical Simulations For AGN

In PSK, we calculated a few disk wind models for the mass of the non-rotating black hole,  $M_{BH} = 10^8 M_\odot$ . To determine the radiation field from the disk, we assumed the mass accretion rate  $\dot{M}_a = 1.8 M_\odot \text{ yr}^{-1}$ . These system parameters yield the disk Eddington number,  $L_D/L_E \equiv \Gamma_D = 0.5$  and the disk inner radius,  $r_* = 8.8 \times 10^{13} \text{ cm}$ . For the radiation field from the central engine, we assumed that one half to the central engine luminosity is radiated in the UV and the other half in X-rays. The total central engine luminosity was assumed equal to the accretion disk luminosity. To calculate the gas temperature, we assumed the temperature of the X-ray radiation,  $T_X = 10 \text{ KeV}$  (see PSK for more details).

Figure 1. A map of the velocity field (the poloidal component only) for the line-driven wind from a disk accreting on a  $10^8 M_\odot$  black hole (PSK's Fig. 2). The rotation axis of the disk is along the left hand vertical frame, while the mid-plane of the disk is along the lower horizontal frame. The position on the figure is expressed in units of the disk inner radius (e.g.,  $100 r_* = 8.8 \times 10^{15}$  cm).



For a fixed disk atmosphere and central radiation source, the most important parameter of the PSK model is the wind X-ray opacity  $\kappa_X$  that determines the optical depth for the X-rays from the central object,  $\tau_X$ .

Figure 1 presents the poloidal velocity of the PSK wind model for the X-ray opacity  $\kappa_X = 40 \text{ g}^{-1} \text{ cm}^2$  for the photoionization parameter  $\xi \equiv 4\pi F_X/n < 10^5$  and  $\kappa_X = 0.4 \text{ g}^{-1} \text{ cm}^2$  otherwise. Here  $F_X$  is the local X-ray flux and  $n$  is the number density of the gas. The UV wind opacity,  $\kappa_{UV}$  was assumed  $0.4 \text{ g}^{-1} \text{ cm}^2$  for all  $\xi$ . The arrows in Figure 1 show that the gas streamlines are perpendicular to the disk over some height that increases with radius. The streamlines then bend away from the central object and converge. The region where the flow is moving almost radially outward is associated with a high-velocity, high density stream. PSK's calculation follows (i) a hot, low density flow with negative radial velocity in the polar region (ii) a dense, warm and fast equatorial outflow from the disk, (iii) a transitional zone in which the disk outflow is hot and struggles to escape the system.

PSK found that the local disk radiation can launch a wind from the disk despite strong ionizing radiation from the central object. The central radiation may overionize the supersonic portion of the flow and severely reduce the wind velocity. To produce a fast disk wind the X-ray opacity must be higher than the UV opacity by a factor  $\gtrsim 100$  for the photoionization parameter  $\xi < 10^5$ . For lower relative X-ray opacity (i.e.,  $\kappa_X/\kappa_{UV} < 100$ ), the gas can be still launched from the disk by the UV disk radiation but the gas velocity never exceeds the escape velocity. To radially accelerate the gas lifted by the local disk radiation, the column density,  $N_H$  must be large enough to reduce the X-ray radiation but not too large to reduce the UV flux from the central engine. In other words, this requires  $\tau_X > 1$  and at the same time,  $\tau_{UV} \ll 1$ .

Our disk wind model can explain many aspects of AGN outflows. For example, the fast stream with the terminal velocity of  $\sim 15000 \text{ km s}^{-1}$  can be identified as a BAL region in QSOs. The stream density and column density are comparable to those observed in BAL QSOs. Because the stream is narrow, BALs should be seen only for a narrow range of inclination angles. Synthetic line profiles calculated based of this model confirm that the model can explain the observations (Proga 2001, in preparation). In particular, the line profiles strongly vary with the inclination angle. The fast stream can produces a strong, broad and blue-shifted absorption component, and even multi-trough structure.

Additionally, our model illustrates that terminal velocity of line-driven winds does not have to be coupled to  $v_{esc}$ , it can be much smaller as in the transient zone in which the disk outflow is overionized and loses support from the line force. It is possible that this slow inner flow, launched and driven by radiation, can explain warm absorbers and outflows in the Seyfert I galaxies.

Let us return to the problem of launching a wind in the presence of X-rays: when can gas be lifted from the disk by the local UV radiation instead of being heated and overionized by the X-ray radiation? This question can be qualitatively answered in terms of the CAK model developed to study stars; results from PSD98 for disks showed that this approach is reasonable. For a given  $L_E$ , the stronger the UV radiation from the disk, the higher the wind mass-loss rate and subsequently the wind density. If we assume fixed X-ray radiation and no X-ray attenuation, we will find that if the UV radiation is strong enough, it can launch a wind of so high density that the X-rays will be unable to ionize the wind. The density of ionizing photons is simply too low compared to the gas density, in other words the photoionization parameter will be low. The X-ray attenuation becomes essential when gas accelerates because the gas density decreases and eventually the X-ray may overionize the gas.

The line force is not always strong enough to push gas of sufficiently high density. To examine in more detail what happens then, it is helpful to consider low mass X-ray binaries (LMXBs). LMXBs resemble AGN in a few respects, for example, in their X-ray/bolometric luminosity ratios. Recent calculations by PK found that in the case of LMXBs, the local disk radiation cannot launch a wind from the disk because of strong ionizing radiation from the central object. Unphysically high X-ray opacities ( $\kappa_X \geq 10^5 \text{ g}^{-1} \text{ cm}^2$ ) are required to shield the UV emitting disk and to allow the line force to drive a disk wind. However the same X-ray radiation that inhibits line driving heats the disk and can produce a hot bipolar wind or corona above the disk. PK's results are consistent with the UV observations of LMXB which show no obvious spectral features associated with strong and fast disk winds.

### 3. A Few Remarks

An important aspect of studying AGN outflows is to understand why some AGN of the same type have outflows and some do not (e.g., QSOs with and without broad absorption lines, BALs), and why different types of AGN have outflows of different appearance (e.g., narrow UV absorption lines in the Seyfert I galaxies and BALs in QSOs). The talks and posters of this workshop have provided many wonderful examples of the variety of outflows in AGN. To address the problem of AGN outflows in general, I will build upon theoretical results for line-driven winds I have discussed so far. Fortunately, the 2-D hydrodynamical models can be understood fairly well using concepts from the original CAK model and the 2-D results can be approximated by analytic formulae.

For example, it is possible to derive analytic formulae to estimate the photoionization parameter at the base of a line-driven disk wind (PK). PK compared results of line-driven disk wind models for accretion disks in LMXBs and AGN. They found that the key parameter determining the role of the line force is not merely the presence of the luminous UV zone in the disk and the presence of

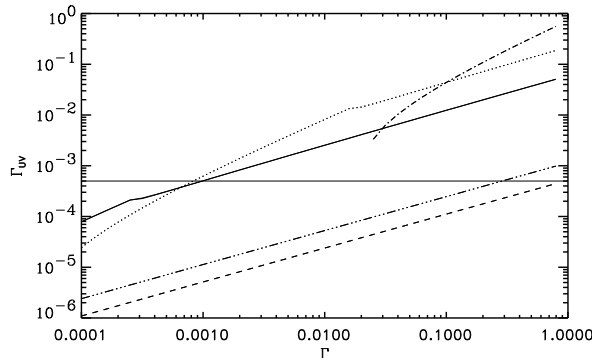


Figure 2. The UV Eddington number as a function of the total Eddington number for AGN, CVs, LMXBs, GBHs and FU Ori stars. See the text for the explanation of the lines.

X-rays, but also the distance of this zone from the center. This result is not surprising because the closer the UV zone to the center, the higher the UV contribution to the total luminosity. That in turn implies a stronger line force and subsequently a denser disk wind launched by the line force. As I already mentioned, the density of the disk wind critically determines whether the wind will stay in a lower ionization state in the presence of X-ray radiation and be further accelerated by the line force to supersonic velocities. Therefore in a general case, we ought to consider not only the total luminosity but also the UV luminosity,  $L_{UV}$  as well as the Eddington number of the UV emitting part of the disk,  $\Gamma_{UV}$ . The UV disk radiation is the one that is to drive a wind, the remaining disk radiation has either little impact on the wind (i.e., the optical and infrared radiation of cold disk) or can reduce the line driving (i.e., X-rays of a hot disk). Simply put, the difference,  $(1 - \Gamma_{UV})L$  is the luminosity that can 'damage' a wind emerging from the UV disk.

Figure 2 shows the UV Eddington number,  $\Gamma_{UV}$  as a function of the total Eddington number,  $\Gamma$  for various accreting objects: massive black hole ( $M_{BH} = 10^8 M_\odot$ , the dotted line), stellar black hole ( $M_{BH} = 10 M_\odot$ , the triplet dot-dashed line), neutron star ( $M_{NS} = 1.4 M_\odot$  the dashed line), white dwarf ( $M_{WD} = 0.6 M_\odot$  the solid line), and low mass young stellar object ( $M_{YSO} = 0.2 M_\odot$  the dot-dashed line). Note that for fixed mass and radius of the accreting object,  $\Gamma$  is proportional to the mass accretion rate. For simplicity, I estimate  $L_{UV}$  by integrating the disk intensity over the disk surface of the effective temperature between 8,000 K and 50,000 K. Detailed photoionization calculations are needed to determine what is a contribution to the line force from radiation at the temperatures beyond this range. To calculate the disk intensity and temperature I used the standard Shakura & Sunyaev disk model (Shakura & Sunyaev 1973). I define the UV Eddington number as the ratio between  $L_{UV}$  and  $L_E$ . The solid horizontal line marks the UV Eddington number above which line driving can drive a wind if there are no X-rays in a system,  $\Gamma_{UV}(M_{max} + 1) < 1$ . Inclusion of X-rays will move this line up because the X-rays will reduce  $M_{max}$ .

Figure 2 allows an easy identification of objects capable of driving winds by lines. They are accretion disks around: massive black holes and white dwarfs

(AGN and CVs with  $\Gamma \gtrsim 0.001$ ) and low mass young stellar object (FU Ori stars with  $\Gamma \gtrsim$  a few  $\times 0.01$  !!!). The systems that have too low  $\Gamma_{UV}$  to drive wind are accretion disks around low mass compact objects (LMXB and galactic black holes, GBH). My classification of objects is consistent with the observations in the sense that the objects I identified as capable of driving winds have been observed to have winds whereas the objects with too low  $\Gamma_{UV}$  do not exhibit strong spectral features associated with winds. Additionally my conclusions based on this simple figure are consistent with detailed numerical calculations (those for FU Ori and GBH have not been published). I do not claim here that UV driving can fully explain the observed outflows but simply make a point that UV driving can drive some winds.

The lesson from the above exercise is that if we repeat it for AGN of different masses of the black hole and different luminosities (subdivided to the UV and X-rays) we can gain some insight into the nature of all AGN outflows.

Future work in hydrodynamical simulations of mass outflows can only benefit from simple analyses such as this. In fact, there are a few difficult problems that one encounters while making theoretical studies. For example, it is hard to make detailed photoionization calculations in connection with multidimensional time dependent calculations. However such photoionization calculations are crucial to confirm if the UV and X-ray opacities are such that the corresponding optical depths are as required. Future work on hydrodynamical models should include modeling the disk internal structure while modeling disk winds. An important limitation of the PSK approach is that it is valid for the gas pressure dominated disk. PSK did not include in their calculations the whole UV disk because its inner part is likely radiation dominated. Nevertheless they found that the mass-loss rate is about 25% of the assumed mass accretion rate. If we assume that the whole UV disk is gas pressure dominated, the mass loss rate will exceed the mass accretion rate by a factor of 10 or more. Does this result mean that the line force can drive such a strong wind that it can significantly change accretion on a black hole? If this is true then it would be very interesting because the models for line-driven disk winds in CVs predict  $\dot{M}_w$  that is too low to completely explain the observations.

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